



TITLE:

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Bearing capacity analysis of transmission tower foundation on slope crest

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1. Introduction

Reverse T-shaped foundation is widely used as transmission tower foundation (Fig. 1). According to the conventional design code by “Electric Technology Research Association”(ETRA), the following Terzaghi’s bearing capacity formula is recommended for calculating the bearing capacity of reverse T-shaped foundation for level ground [1]:

$$q_u = \alpha c N_c + \beta \gamma_1 B N_\gamma + \gamma_2 D_f N_q, \quad (1)$$

where q_u denotes the ultimate bearing capacity of footing on a level ground, N_c, N_γ, N_q denote the bearing capacity factors, which depend on internal friction angle ϕ of the ground soil. c denotes the soil cohesion, γ_1 the unit weight of soil below foundation base, γ_2 the unit weight of soil above foundation base, α and β , the shape factors for three-dimensional effects, B the foundation width, D_f the depth of foundation. However, in using Eq.(1) to calculate the bearing capacity of foundations with relatively deep embedment, like reverse T-shaped foundation, the following two issues need to be considered: (1) Although the third term of Eq.(1) means the effect of embedment depth or overburden load, it is mainly intended for shallow foundations. Straightforward application of Terzaghi’s formula for calculating the bearing capacity of foundations with relatively deep embedment has not been verified in past studies. (2) Equation (1) is originally developed for two-dimensional strip footing foundations, while it is extended to foundation having three-dimensional shapes, such as rectangular and circular footings, by introducing shape factors α and β . However, the effect of three-dimensional shape in deeply embedded cases, like reverse T-shaped foundation, may not be expressed properly.

Further, because the bearing capacity of foundations embedded in slope ground would decrease compared with level ground, ETRA recommends the use of a reduction coefficient ζ_s for proper evaluation of the bearing capacity of foundation on a slope;

namely, $q'_u = \zeta_s \cdot q_u$, where q_u is the bearing capacity in a slope ground. Values of the reduction coefficient ζ_s for various slope conditions were obtained by Kusakabe et al.[2] using numerical analysis based on upper bound theorem. As shown in Fig.2, the slope angle, the width of foundation, the height of slope and the distance from the base of foundation to slope surface, as well as the soil property represented by c , ϕ , and γ , are considered in calculation. But since this reduction rate is only for shallow foundation, for relatively deep embedment, ETRA recommends an adjustment of foundation embedment, according to a positional relationship between foundation and slope face.

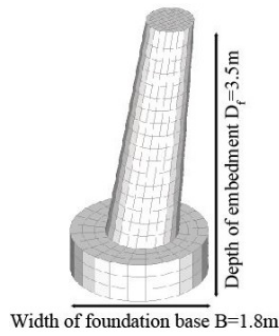


Figure 1: Analysis model for a “18-35” standard-sized reverse T-shaped foundation

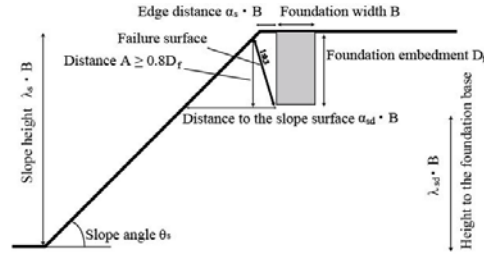


Figure 2: Slope ground parameters

In this research, two- and three-dimensional finite element analyses are performed to examine the bearing capacity of transmission tower foundation embedded on a slope crest. The edge distance from the slope crest to the foundation would affect the bearing capacity significantly. Hence, a particular focus is paid for reduction of bearing capacity when the foundation is embedded close to the slope crest. The effects of the slope angle, slope height, and soil property are also examined. Further, relationship between the bearing capacity and the mechanism of ground failure is discussed in detail. The analysis results are then compared with the result calculated by ETRA formula.

2. Methods

Two-dimensional analysis for a strip foundation and three-dimensional analysis for reverse T-shaped foundation were examined for verifying the bearing capacity of foundation embedded on a slope crest. The results were then compared with the level ground to examine the influence of edge distance on the bearing capacity. Two models of the two-dimensional strip foundation and three-dimensional reverse T-shaped foundation embedded on a slope ground are shown in Fig. 3 and Fig. 4, respectively. A series of elastoplastic FEA using Mohr-Coulomb and Drucker-Prager plasticity models were performed. The parameters for soil property are set to be $c=15.876\text{kPa}$ and $\phi = 10^\circ$ throughout the analysis.

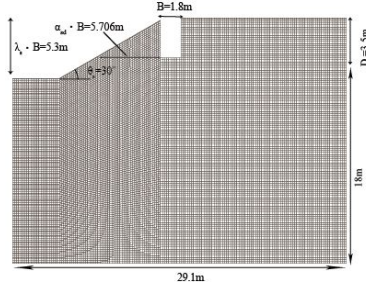


Figure 3: 2D FEA analytic model

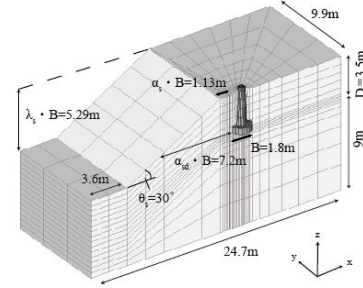


Figure 4: 3D FEA analytic model

3. Results

(i) FEA of 2D strip foundation

Fig. 5(a) and (b) show the bearing capacity and bearing capacity reduction ratio q'_u / q_u as a function of the normalized edge distance α_{sd} , respectively. Here, the bearing capacity reduction ratio is defined as the ratio of the bearing capacity in slope to that in level ground. Both the bearing capacity and bearing capacity reduction ratio decreased as the edge distance is decreased, particularly the FEA results of bearing capacity reduction ratio is much lower than ETRA estimation when $\alpha_{sd} \leq 10$. According to ETRA formula, in the case of $\lambda_{sd} = 1$, the bearing capacity in the slope ground is equivalent to that in the level ground when level ground when $\alpha_{sd} \geq 4.7$. However, FE analysis shows that much larger edge distance $\alpha_{sd} \geq 10$ is required to secure the bearing capacity equivalent to the level ground. This result implies that the influence of edge distance on the bearing capacity reduction ratio may be underestimated by the current design code recommended by ETRA.

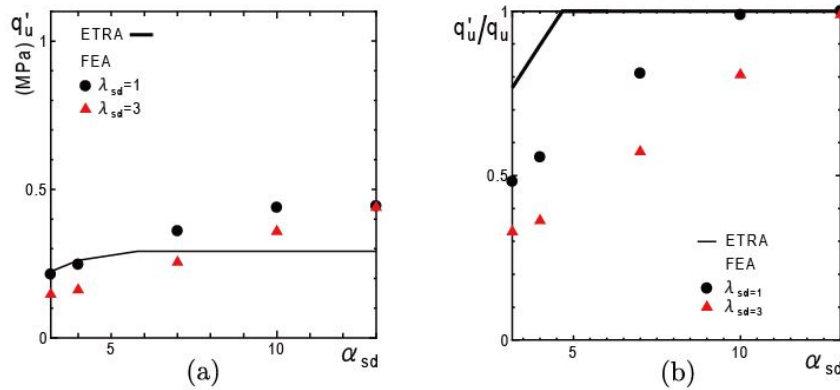


Figure 5: Effect of edge distance on bearing capacity (a) and bearing capacity reduction ratio (b) of 2D strip foundation

In order to examine the mechanical cause of the reduction of bearing capacity due to slope effect, Fig.6 shows the shear strain distribution at the failure point in level ground and slope ground for the case of $\lambda_{sd} = 1$. As mentioned above, according to ETRA estimation, the bearing capacity in a slope ground of the present geometry setting is nearly equivalent to that in the level ground when $\alpha_{sd} \geq 4.7$. However, Fig. 6(b), (c), and (d) show a band-shaped circular or curved slip failure developing from the edge of foundation

base toward the slope toe. Such widely distributed ground failure can be regarded as an essential factor of the reduction of bearing capacity in slope grounds. On the other hand, in Fig. 6(e) the slope ground of $\alpha_{sd} = 13$ exhibits a bilaterally symmetric failure similar to the level ground. This result is consistent with the fact that, as shown in Fig.5, the bearing capacity equivalent to the level ground can be secured when $\alpha_{sd} \geq 13$ without being affected by edge distance. The above result demonstrates that the bearing capacity significantly decreases when the foundation is embedded close to a slope crest with an edge distance smaller than a certain value. More importantly, FE analysis result shows that the edge distance required to secure the bearing capacity equivalent to the level ground is much larger than the ETRA estimation. This discrepancy is crucial and hence will further be discussed in 3D analysis.

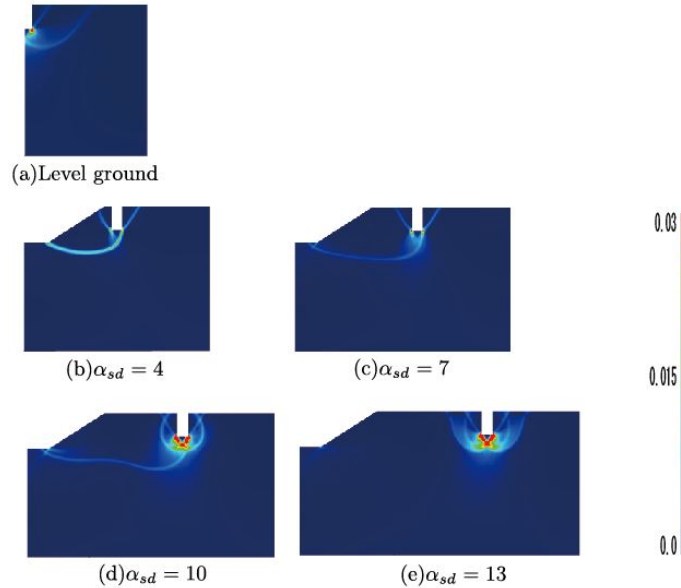


Figure 6: 2D strip foundation shear distribution in slope ground

(ii) FEA of 3D reverse T-shaped foundation

Fig. 7(a) presents the relationship between load and vertical displacement obtained by 3D FEA for reverse T-shaped foundation. The same trend as 2D FEA for strip foundation was obtained: bearing capacity decreases when α_{sd} is decreased. One can also observe in Fig. 7(b) that FEA result is almost three times as large as ETRA result. In Fig. 7(c) shows the relationship between q'_u / q_u and α_{sd} . 3D FEA result is slightly lower than ETRA estimation but it is still higher than 2D FEA result when $\alpha_{sd} < 7$. In Fig. 7(c), 3D FEA results exhibit the bearing capacity equivalent to that of level ground when $\alpha_{sd} > 7$. Moreover, 3D FEA obtained a greater value of q'_u / q_u than 2D FEA, and it is much closer to the ETRA's estimation. This is in contrast to the result observed in 2D analysis $\alpha_{sd} \geq 10$ is required for 2D strip foundation to avoid the slope effect. From the above results, the edge distance is less influential on 3D reverse T-shaped foundation than on 2D strip foundation. Fig. 7(d) presents the distribution of shear strain around reverse T-shaped foundation for $\alpha_{sd} = 4$. The band shaped circular failure observed in Fig. 6(b) for two-dimensional case was not seen in Fig. 7(d).

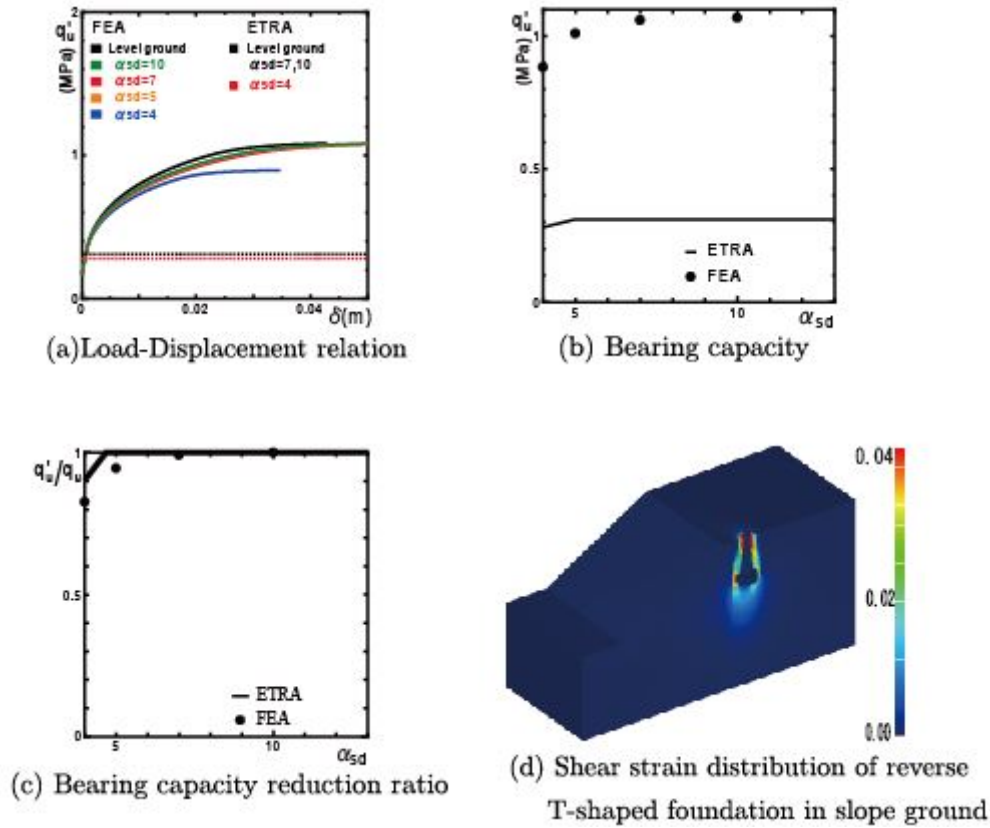


Figure 7: 3D FEA result for reverse T-shaped foundation

4. Conclusions

Regarding the reduction of bearing capacity due to slope effect, 2D strip foundation indicates a greater effect range and influence than the estimation based on the design code recommended by ETRA. However, FE result for the bearing capacity of 2D strip foundation is generally the same or greater than the estimation by ETRA formula, which means ETRA formula can be regarded as safe side. Further, such tendency is more remarkable in FE result for 3D reverse T-shaped foundation.

Acknowledgements

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